“All our work, our whole life is a matter of **semantics**, because words are the tools with which we work, the material out of which laws are made, out of which the Constitution was written. Everything depends on our understanding of them.”
–Felix Frankfurter

Semantic Analysis

Having figured out the program’s structure, now figure out what it means

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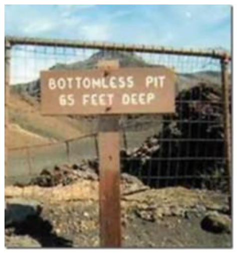

$\forall$i, j: i < j $\Rightarrow$ A[i] $\leq$ A[j]

Fortran

```
ZERO = 0
SNORK(ZERO,X,Y)
```

Semantic Analysis/Checking

- Semantic analysis: the final part of analysis
- Purposes include
  – perform final checking of legality of input program, not captured by lexical and syntactic checking
  – name resolution, type checking, ...
  – “understand” program well enough to do synthesis
    - primarily, relate assignments to and references of a particular variable

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Symbol Tables

- Key data structure during semantic analysis, code generation
- Build in semantic pass
- Stores information about the names used in program
  – a map (table) from names to information about them
  – each symbol table entry is a binding
  – a declaration adds a binding to the map
  – a use of a name looks up binding in the map
  – report an error if none found

An Example

```
class C {
   int x;
   boolean y;
   int f(C c) {
       int z;
       ...
       ...z...c...new C()...x...f(..)...
   }
}
```

A Bigger Example

```
class C {
   int x;
   boolean y;
   int f(C c) {
       int z;
       ...
       {
          boolean x;
          C z;
          int f;
          ...z...c...new C()...x...f(...)...
       }
     ...z...c...new C()...x...f(...)...
     }
}
```

Nested Scopes

- Can have same name declared in different scopes
  - Why?
- References use closest textually-enclosing declaration
  - static/lexical scoping, block structure
  - closer declaration shadows declaration of enclosing scope

Approach

- Simple solution
  - one symbol table per scope
  - each scope's symbol table refers to its lexically enclosing scope's symbol table
  - root is the global scope's symbol table
  - look up declaration of name starting with nearest symbol table, proceed to enclosing symbol tables if not found locally
- All scopes in program form a tree

Name Spaces

- One name may unambiguously refer to different things

```
class F {
  int F(F F) {// 3 different F's
     ... new F() ...
     ... F = ...
     ... this.F(...) ...
  }
}
```

- MiniJava has three name spaces: classes, methods, and variables
  - We always know which we mean for each name reference, based on its syntactic position
  - So, have the symbol table store a separate map for each name space

Information About Names

- Different kinds of declarations store different information about their names
  - must store enough information to be able to check later references to the name
- A variable declaration:
  - its type
  - whether it's final, etc.
  - whether it's public, etc.
  - (maybe) whether it's a local variable, an instance variable, a global variable, or ...

Information About Names

- A method declaration:
  - its argument and result types
  - whether it's static, etc.
  - whether it's public, etc.
- A class declaration:
  - its class variable declarations
  - its method and constructor declarations
  - its superclass

Generic Type Checking Algorithm

- Recursively type check each of the nodes in the program's AST, each in the context of the symbol table for its enclosing scope
  - going down, create any nested symbol tables and context needed
  - recursively type check child subtrees
  - on the way back up, check that the children are legal in the context of their parents

Method per AST node class

- Each AST node class defines its own type check method, which fills in the specifics of this recursive algorithm
- Generally
  - declaration AST nodes add bindings to the current symbol table
  - statement AST nodes check their subtrees
  - expression AST nodes check their subtrees and return a result type

MiniJava

- Various SymbolTable classes, organized into a hierarchy

```
SymbolTable
  GlobalSymbolTable
  NestedSymbolTable
    ClassSymbolTable
    CodeSymbolTable
```

- Support operations such as

```
declareClass, lookupClass
declareInstanceVariable,
    declareLocalVariable,
    lookupVariable
declareMethod, lookupMethod
```

Stored Information

- `lookupClass` returns a `ClassSymbolTable`
  - includes all the information about the class's interface
- `lookupVariable` returns a `VarInterface` to store the variable's type
- A hierarchy of implementations:
  - `VarInterface`
  - `  LocalVarInterface`
  - `  InstanceVarInterface`
- `lookupMethod` returns a `MethodInterface`
  - To store the method's argument and result types

Key AST Type Check Operations

- `void Program.typecheck()`
  `throws TypecheckCompilerExn;`
  - type check whole program
- `void Stmt.typecheck(CodeSymbolTable)`
  `throws TypecheckCompilerExn;`
  - type check a statement using a given symbol table
- `ResolvedType Expr.typecheck(CodeSymbolTable)`
  `throws TypecheckCompilerExn;`
  - type check an expression using a given symbol table, returning the type of the result

Forward References

- Type checking class declarations is tricky: need to allow for forward references from the bodies of earlier classes to the declarations of later classes

```
class First {
   Second next;      // must allow this forward ref
   int f() {
   ... next.g() ...  // and this forward ref
   }
}
class Second {
   First prev;
   int g() {
      ... prev.f() ...
   }
}
```

Supporting Forward References

- So, type check a program's class declarations in multiple passes
- first pass: remember all class declarations
  - {`First -->` class`{?}`, `Second -->`class`{?}`}
- second pass: compute interface to each class, checking class types in headers
  - {`First -->` class`{next:Second}`,
  - `Second -->`class`{prev:First}`}
- third pass: check method bodies, given interfaces

Supporting Forward References

```
void ClassDecl.declareClass(GlobalSymbolTable)
      throws TypecheckCompilerExn;
```

- declare the class in the global symbol table

```
void ClassDecl.computeClassInterface()
      throws TypecheckCompilerExn;
```

- fill out the class's interface, given the declared classes

```
void ClassDecl.typecheckClass()
      throws TypecheckCompilerExn;
```

- type check the body of the class, given all classes' interfaces

Example Type Checking Operation

```
class VarDeclStmt {
  String name;
  Type type;

   void typecheck(CodeSymbolTable st)
      throws TypecheckCompilerExn {
  st.declareLocalVar(type.resolve(st), name);
  }
}
```

- `resolve` checks that a syntactic type expression is legal, and returns the corresponding resolved type
- `declareLocalVar` checks for duplicate variable declaration in this scope

Example Type Checking Operation

```
class AssignStmt {
   String lhs;
   Expr rhs;
   void typecheck(CodeSymbolTable st)
      throws TypecheckCompilerException {
     VarInterface lhs_iface = st.lookupVar(lhs);
     ResolvedType lhs_type = lhs_iface.getType();
     ResolvedType rhs_type = rhs.typecheck(st);
     rhs_type.checkIsAssignableTo(lhs_type);
     }
   }
```

- `lookupVar` checks that the name is declared as a var
- `checkIsAssignableTo` verifies that an expression yielding the rhs type can be assigned to a variable declared to be of lhs type

Example Type Checking Operation

```
class IfStmt {
   Expr test;
   Stmt then_stmt;
   Stmt else_stmt;
   void typecheck(CodeSymbolTable st)
        throws TypecheckCompilerException {
     ResolvedType test_type = test.typecheck(st);
     test_type.checkIsBoolean();
     then_stmt.typecheck(st);
     else_stmt.typecheck(st);
   }
}
```

Example Type Checking Operation

```
class BlockStmt {
   List<Stmt> stmts;
   void typecheck(CodeSymbolTable st)
        throws TypecheckCompilerException {
      CodeSymbolTable nested_st =
          new CodeSymbolTable(st);
      foreach Stmt stmt in stmts {
          stmt.typecheck(nested_st); }
   }
}
```

- (Garbage collection will reclaim `nested_st` when done)

Example Type Checking Operation

```
class IntLiteralExpr extends Expr {
  int value;

  ResolvedType typecheck(CodeSymbolTable st)
       throws TypecheckCompilerException {
    return ResolvedType.intType();
  }
}
```

`ResolvedType.intType()` returns the resolved int type

Example Type Checking Operation

```
class VarExpr extends Expr {
  String name;

  ResolvedType typecheck(CodeSymbolTable st)
        throws TypecheckCompilerException {
     VarInterface iface = st.lookupVar(name);
     return iface.getType();
  }
}
```

Example Type Checking Operation

```
class AddExpr extends Expr {
   Expr arg1;
   Expr arg2;

   ResolvedType typecheck(CodeSymbolTable st)
         throws TypecheckCompilerException {
      ResolvedType arg1_type =
                    arg1.typecheck(st);
      ResolvedType arg2_type =
                    arg2.typecheck(st);
      arg1_type.checkIsInt();
      arg2_type.checkIsInt();
      return ResolvedType.intType();
    }
}
```

Polymorphism and Overloading

- Some operations are defined on multiple types
- Polymorphism occurs when a single operation means and behaves the same while working with different types
  - Ex: Length of a list in ML or such is polymorphic: it doesn't care what the elements of the list are
  - Ex: Assignment can assign any compatible left-hand and right-hand sides
- Overloading occurs when a single operator has (usually) similar meanings with different implementations
  - Ex: Comparing ints and bools for equality
  - Ex: Ordering ints and strings

Polymorphism and Overloading

- Full Java allows methods and constructors to be overloaded, too
  - different methods can have same name but different argument types
- Java 1.5 supports (parametric) polymorphism via generics: parameterized classes and methods
- This all makes type checking more complicated. (So why do we allow it?)

An Example Overloaded Type Check

```
class EqualExpr extends Expr {
   Expr arg1;
   Expr arg2;
   ResolvedType typecheck(CodeSymbolTable st)
         throws TypecheckCompilerException {
      ResolvedType arg1_type = arg1.typecheck(st);
      ResolvedType arg2_type = arg2.typecheck(st);
      if (arg1_type.isIntType() &&
          arg2_type.isIntType()) {
         //resolved overloading to int version
         return ResolvedType.intType();
      } else if (arg1_type.isBooleanType() &&
                 arg2_type.isBooleanType()) {
         //resolved overloading to boolean version
        return ResolvedType.booleanType();
      } else {
      throw new TypecheckCompilerException("bad overload");
}}}
```

MiniJava

- Add resolved type for arrays: parameterized by element type
  - when are two array types equal?
  - when is one a subtype of another?
  - when is one assignable to another?

MiniJava

- **`ForStmt`**
  - loop index variable must be declared to be an **`int`**
  - initializer and increment expressions must be **`int`**s
  - test expression must be a **`boolean`**
- **`BreakStmt`**
  - must be nested in a loop

MiniJava

`ArrayAssignStmt`
- array expr must be an array
- index expr must be an int
- rhs expr must be assignable to array’s element type

`ArrayLookupExpr`
- array expr must be an array
- index expr must be an int
- result is array’s element type

`ArrayLengthExpr`
- array expr must be an array
- result is an int

`ArrayNewExpr`
- length expr must be an int
- element type must be a legal type
- result is array of given element type

Type Checking Terminology

Static vs. dynamic typing
- static: checking done prior to execution (e.g. compile-time)
- dynamic: checking during execution

Strong vs. weak typing
- strong: guarantees no illegal operations performed
- weak: can’t make guarantees

Caveats:
- Hybrids common
- Inconsistent usage common
- “untyped,” “typeless” could mean dynamic or weak

	static	dynamic
strong	Java	Lisp
weak	C	PERL (1-5)

Type Equivalence

- When is one type equal to another?
  - implemented in MiniJava with **`ResolvedType.equals(ResolvedType)`** method
- “Obvious” for atomic types like **`int`**, **`boolean`**, class types
- What about type "constructors" like arrays?
  - **`int[] a1;`**
  - **`int[] a2;`**
  - **`int[][] a3;`**
  - **`boolean[] a4;`**
  - **`Rectangle[] a5;`**
  - **`Rectangle[] a6;`**

Type Equivalence

- Parameterized types in Java 1.5:
  - **`List<int>l1; List<int>l2; List<List<int>>l3;`**
- In C:
  - **`int* p1; int* p2;`**
  - **`struct {int x;} s1; struct {int x;} s2;`**
  - **`typedef struct {int x;} S; S s3; S s4;`**

Name Equivalence

- *Name equivalence* says that two types are equal iff they came from the same textual occurrence of a type constructor
  - Ex: class types, **`struct`** types in C, datatypes in ML
  - special case: type synonyms (e.g. **`typedef`**) don’t define new types
- Implement with pointer equality of **`ResolvedType`** instances

Structural Equivalence

- In contrast, *Structural equivalence* says two types are equal iff they have same structure
  - atomic types are tautologically the same structure
  - if type constructors:
    - same constructor
    - recursively, equivalent arguments to constructor
- Ex: atomic types, array types, record types in ML
- Implement with recursive implementation of equals, or by canonicalization of types when types created then use pointer equality

Type Conversions and Coercions

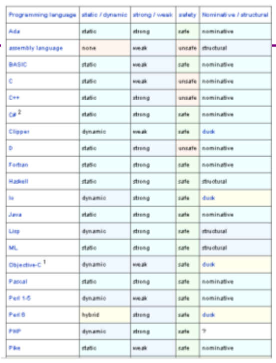
- In Java, can explicitly convert an object of type **`double`** to one of type **`int`**
  - can represent as unary operator
  - typecheck, codegen normally
- In Java, can implicitly coerce an object of type **`int`** to one of type **`double`**
  - compiler must insert unary conversion operators, based on result of type checking

Type Casts

- In most languages, one can explicitly cast an object of one type to another
  - sometimes cast means a conversion (e.g., casts between numeric types)
  - sometimes cast means a change of static type without doing any computation (casts between pointer types or pointer and numeric types)

C and Java: type casts

- In C: safety/correctness of casts not checked
  - allows writing low-level code that's type-unsafe
  - more often used to work around limitations in C's static type system
- In Java: downcasts from superclass to subclass include run-time type check to preserve type safety
    - static typechecker allows the cast
    - codegen introduces run-time check
    - Java's main form of dynamic type checking



Programming language	static / dynamic	strong / weak	safety	Nominative / structural
Ada	static	strong	safe	nominative
assembly language	none	weak	unsafe	structural
BASIC	static	weak	safe	nominative
C	static	weak	unsafe	nominative
C++	static	strong	unsafe	nominative
C# [2]	static	strong	safe	nominative
Clipper	dynamic	weak	safe	duck
D	static	strong	unsafe	nominative
Fortran	static	strong	safe	nominative
Haskell	static	strong	safe	structural
Io	dynamic	strong	safe	duck
Java	static	strong	safe	nominative
Lisp	dynamic	strong	safe	structural
ML	static	strong	safe	structural
Objective-C [1]	dynamic	weak	safe	duck
Pascal	static	strong	safe	nominative
Perl 1-5	dynamic	weak	safe	nominative
Perl 6	hybrid	strong	safe	duck
PHP	dynamic	strong	safe	?
Pike	static	weak	safe	nominative